US010120448B2

(12) **United States Patent**
Hajati

(10) **Patent No.: US 10,120,448 B2**
(45) **Date of Patent: *Nov. 6, 2018**

(54) **METHOD OF TUNING A HAPTIC ACTUATOR INCLUDING FERROMAGNETIC MASS CHANGE ITERATIONS AND RELATED APPARATUS**

(71) Applicant: **Apple Inc.**, Cupertino, CA (US)

(72) Inventor: **Arman Hajati**, Cupertino, CA (US)

(73) Assignee: **APPLE INC.**, Cupertino, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 631 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/819,910**

(22) Filed: **Aug. 6, 2015**

(65) **Prior Publication Data**

US 2017/0038863 A1 Feb. 9, 2017

(51) **Int. Cl.**

H04B 3/36	(2006.01)
G08B 6/00	(2006.01)
G09B 21/00	(2006.01)
G06F 3/01	(2006.01)
G04G 21/00	(2010.01)

(52) **U.S. Cl.**

CPC ***G06F 3/016*** (2013.01); ***G04G 21/00*** (2013.01)

(58) **Field of Classification Search**

CPC G06F 3/016; G08B 6/00; G09B 21/003

USPC 340/407.2

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,369,115 B2 * 5/2008 Cruz-Hernandez G06F 3/016 310/316.01

8,169,402 B2 5/2012 Shahoian et al.

8,780,053 B2 * 7/2014 Colgate G06F 3/016 178/18.04

(Continued)

FOREIGN PATENT DOCUMENTS

WO 2013169299 A1 11/2013

WO 2013169303 A1 11/2013

(Continued)

OTHER PUBLICATIONS

Hajati, Arman, U.S. Appl. No. 14/819,865 filed Aug. 6, 2015.

Product Specification Sheet: Geeplus, VIBRO1 Vibration Actuator, 2 pages, www.geeplus.biz, downloaded on Jul. 15, 2015.

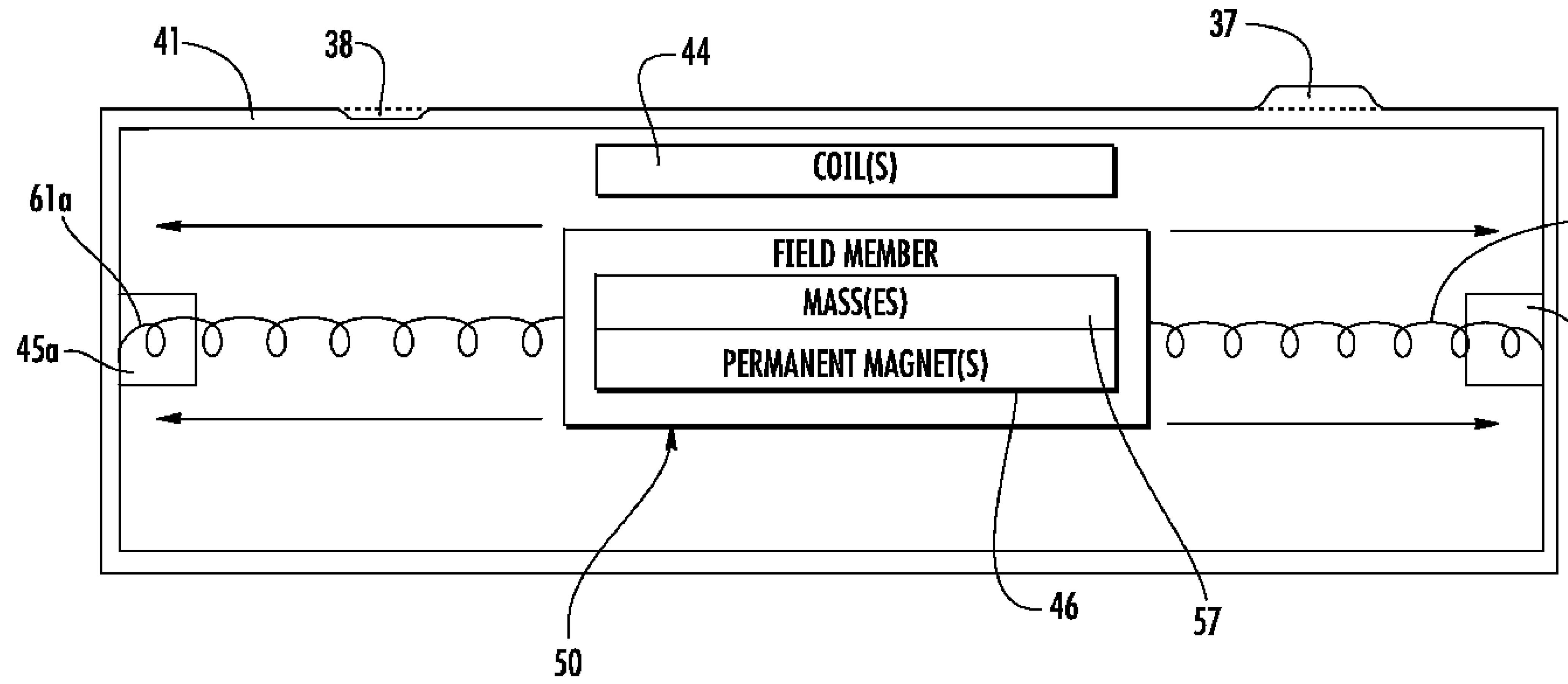
Primary Examiner — John A Tweel, Jr.

(74) *Attorney, Agent, or Firm* — Allen, Dyer, Doppelt + Gilchrist, P.A.

(57) **ABSTRACT**

A method is directed to tuning a haptic actuator that includes a housing having a ferromagnetic mass, a coil carried by the housing, and a field member movable within the housing responsive to the coil. The haptic actuator is operative as a resonator and has an initial quality (Q) factor. The method may include determining whether the initial Q factor is within a desired Q factor range, and when the initial Q factor is not within the desired Q factor range, performing ferromagnetic mass change iterations until an updated Q factor is within the desired Q factor range. Each ferromagnetic mass change iteration may include changing the ferromagnetic mass of the housing, determining the updated Q factor based upon changing the ferromagnetic mass of the housing, and determining whether the updated Q factor is within the desired Q factor range. Another embodiment changes the ferromagnetic mass of the field member.

26 Claims, 12 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

9,564,029	B2 *	2/2017	Morrell	G06F 3/016
9,804,673	B2 *	10/2017	Colloms	G06F 3/016
2014/0197936	A1	7/2014	Biggs et al.	
2015/0109223	A1	4/2015	Kessler et al.	
2015/0116205	A1	4/2015	Westerman et al.	
2015/0130730	A1	5/2015	Harley et al.	
2017/0038840	A1 *	2/2017	Hajati	G06F 3/016

FOREIGN PATENT DOCUMENTS

WO	2013169305	A1	11/2013
WO	2013170099	A1	11/2013
WO	2013188307	A2	12/2013
WO	2014018111	A1	1/2014
WO	2015020663	A1	2/2015

* cited by examiner

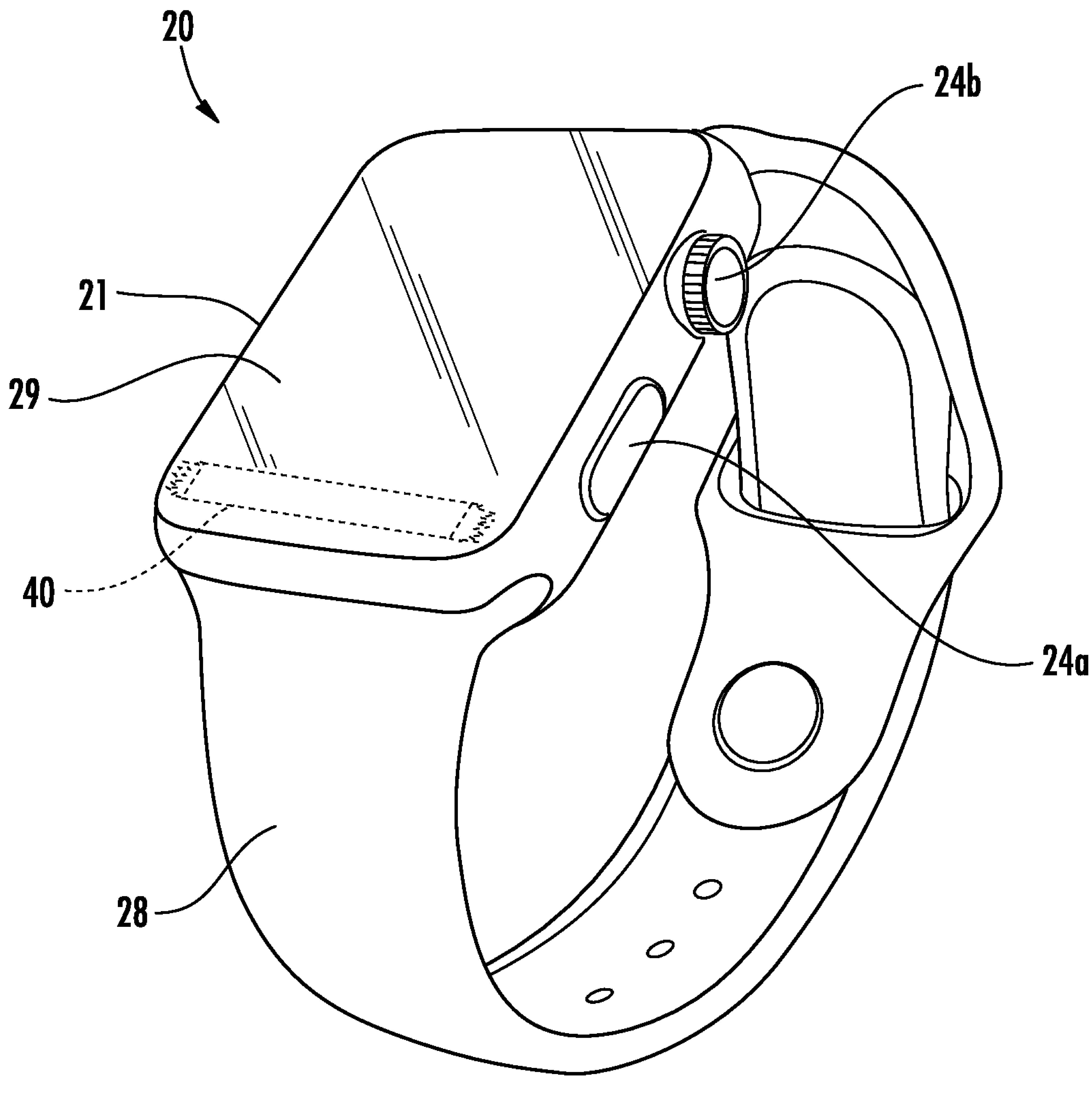


FIG. 1

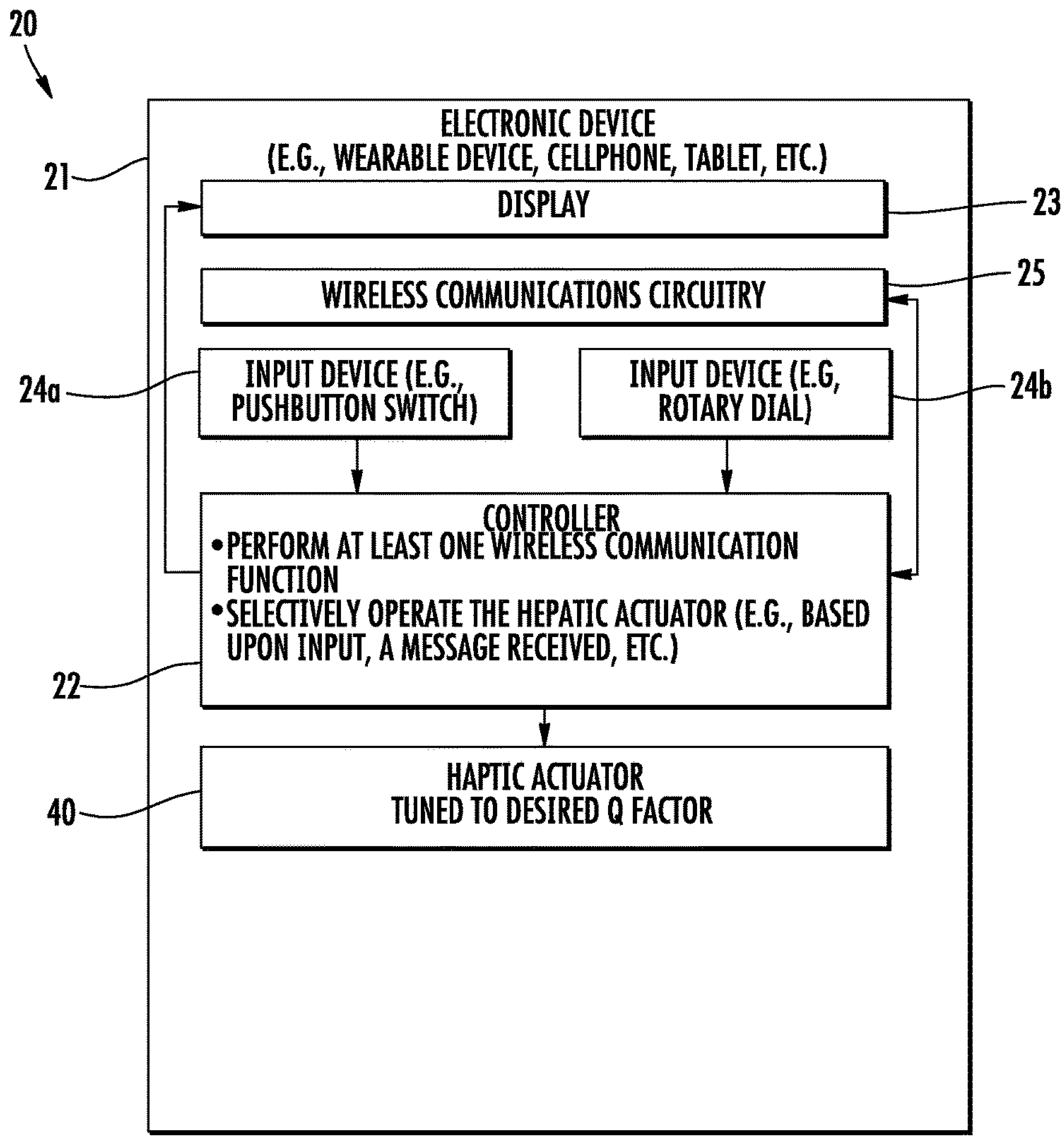

20
21
ELECTRONIC DEVICE
(E.G., WEARABLE DEVICE, CELLPHONE, TABLET, ETC.)
DISPLAY
23
WIRELESS COMMUNICATIONS CIRCUITRY
25
24a
INPUT DEVICE (E.G., PUSHBUTTON SWITCH)
INPUT DEVICE (E.G, ROTARY DIAL)
24b
CONTROLLER
•PERFORM AT LEAST ONE WIRELESS COMMUNICATION FUNCTION
•SELECTIVELY OPERATE THE HEPATIC ACTUATOR (E.G., BASED UPON INPUT, A MESSAGE RECEIVED, ETC.)
22
HAPTIC ACTUATOR
TUNED TO DESIRED Q FACTOR
40

FIG. 2

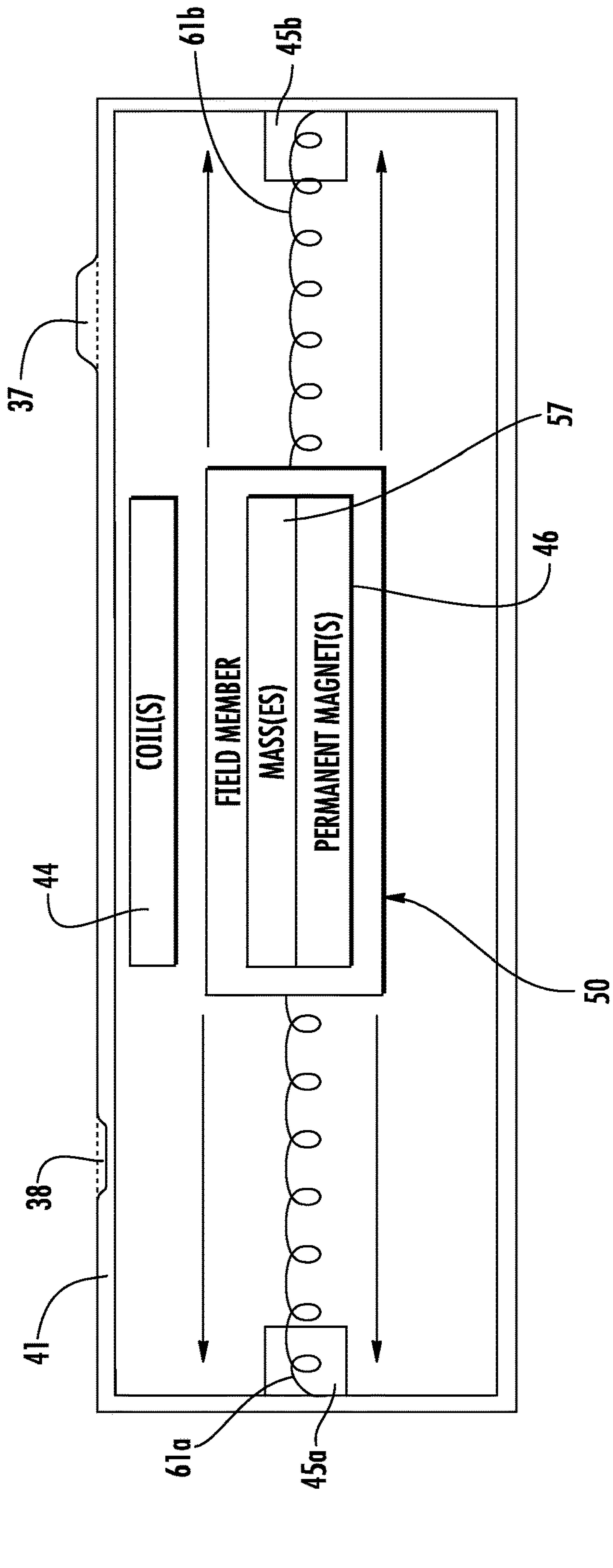

61b
45b
37
57
46
COIL(S)
FIELD MEMBER
MASS(ES)
PERMANENT MAGNET(S)
44
50
38
41
61a
45a

FIG. 3

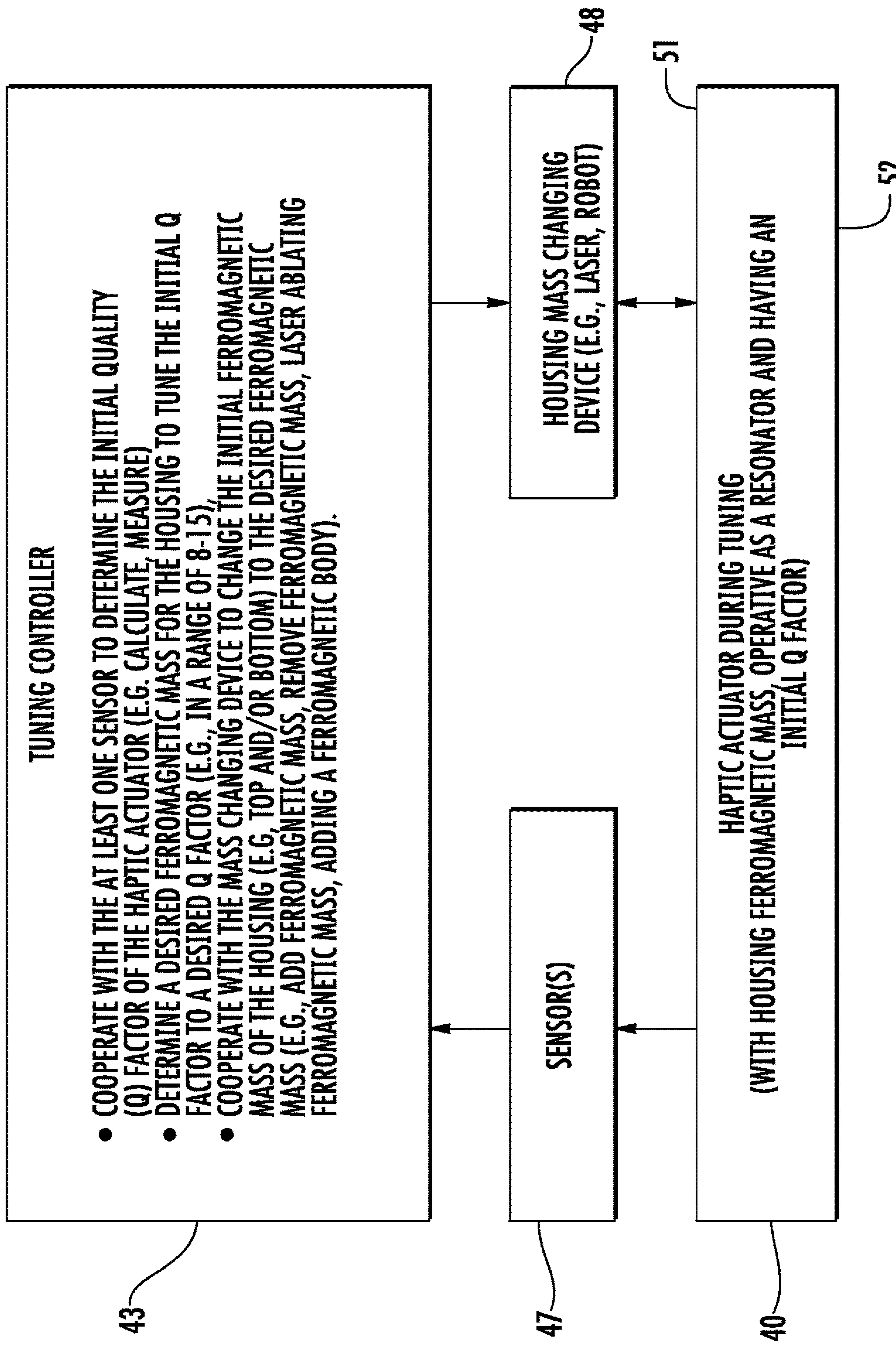

TUNING CONTROLLER
• COOPERATE WITH THE AT LEAST ONE SENSOR TO DETERMINE THE INITIAL QUALITY (Q) FACTOR OF THE HAPTIC ACTUATOR (E.G. CALCULATE, MEASURE)
• DETERMINE A DESIRED FERROMAGNETIC MASS FOR THE HOUSING TO TUNE THE INITIAL Q FACTOR TO A DESIRED Q FACTOR (E.G., IN A RANGE OF 8-15),
• COOPERATE WITH THE MASS CHANGING DEVICE TO CHANGE THE INITIAL FERROMAGNETIC MASS OF THE HOUSING (E.G, TOP AND/OR BOTTOM) TO THE DESIRED FERROMAGNETIC MASS (E.G., ADD FERROMAGNETIC MASS, REMOVE FERROMAGNETIC MASS, LASER ABLATING FERROMAGNETIC MASS, ADDING A FERROMAGNETIC BODY).
43
HOUSING MASS CHANGING DEVICE (E.G., LASER, ROBOT)
48
SENSOR(S)
47
51
52
HAPTIC ACTUATOR DURING TUNING (WITH HOUSING FERROMAGNETIC MASS, OPERATIVE AS A RESONATOR AND HAVING AN INITIAL Q FACTOR)
40

FIG. 4

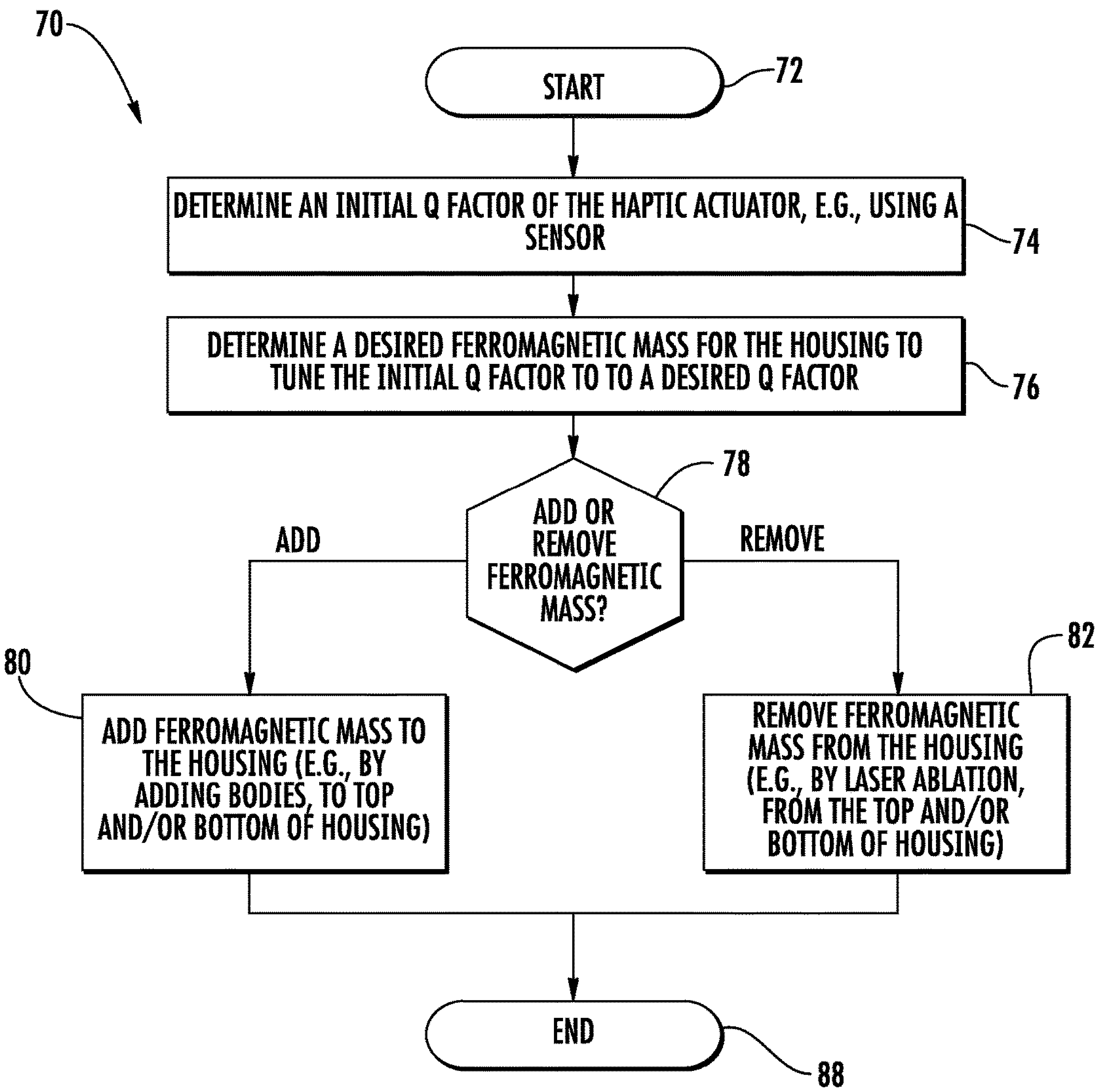

70
START
72
DETERMINE AN INITIAL Q FACTOR OF THE HAPTIC ACTUATOR, E.G., USING A SENSOR
74
DETERMINE A DESIRED FERROMAGNETIC MASS FOR THE HOUSING TO TUNE THE INITIAL Q FACTOR TO TO A DESIRED Q FACTOR
76
ADD OR REMOVE FERROMAGNETIC MASS?
78
ADD
REMOVE
80
ADD FERROMAGNETIC MASS TO THE HOUSING (E.G., BY ADDING BODIES, TO TOP AND/OR BOTTOM OF HOUSING)
82
REMOVE FERROMAGNETIC MASS FROM THE HOUSING (E.G., BY LASER ABLATION, FROM THE TOP AND/OR BOTTOM OF HOUSING)
END
88

FIG. 5

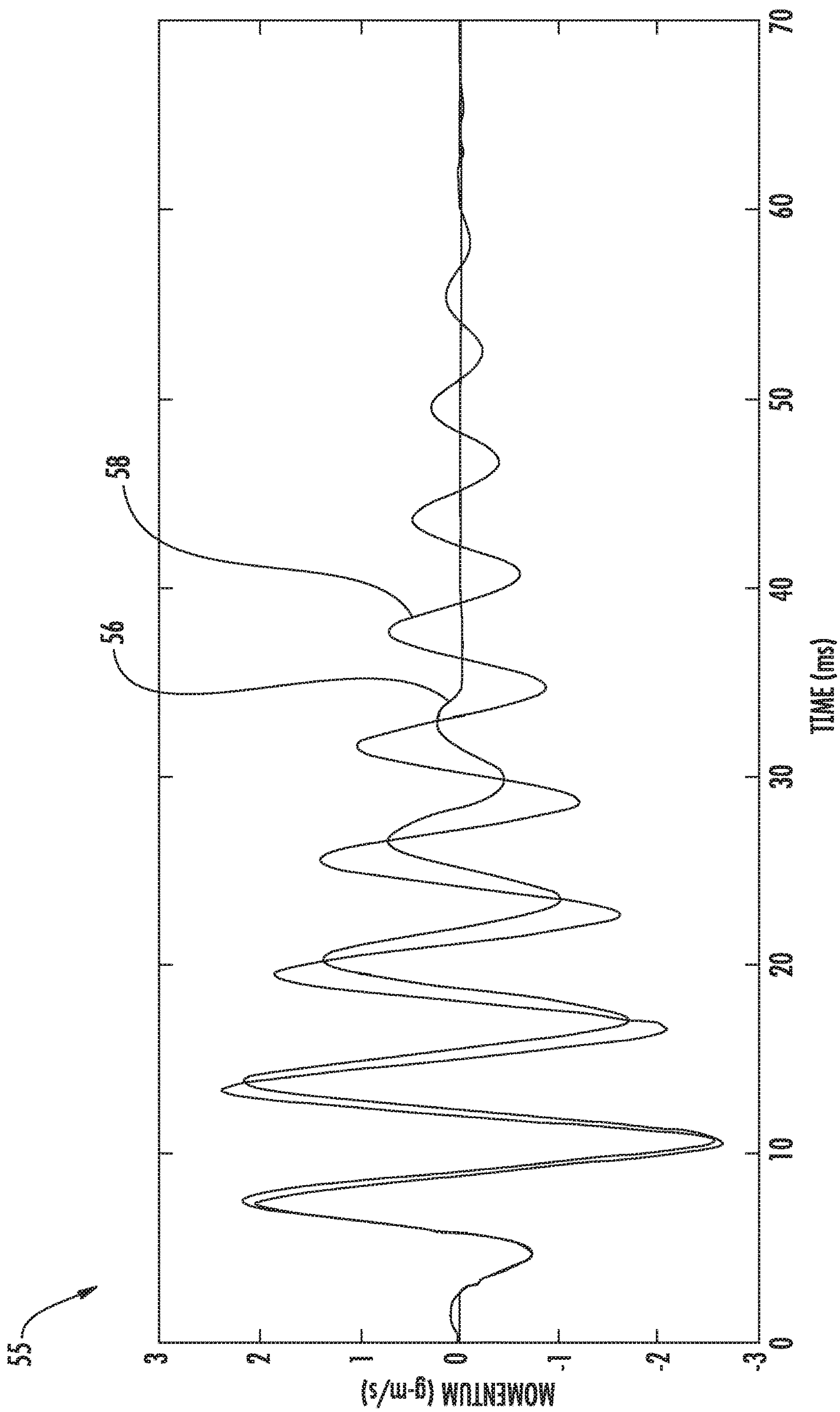


FIG. 6

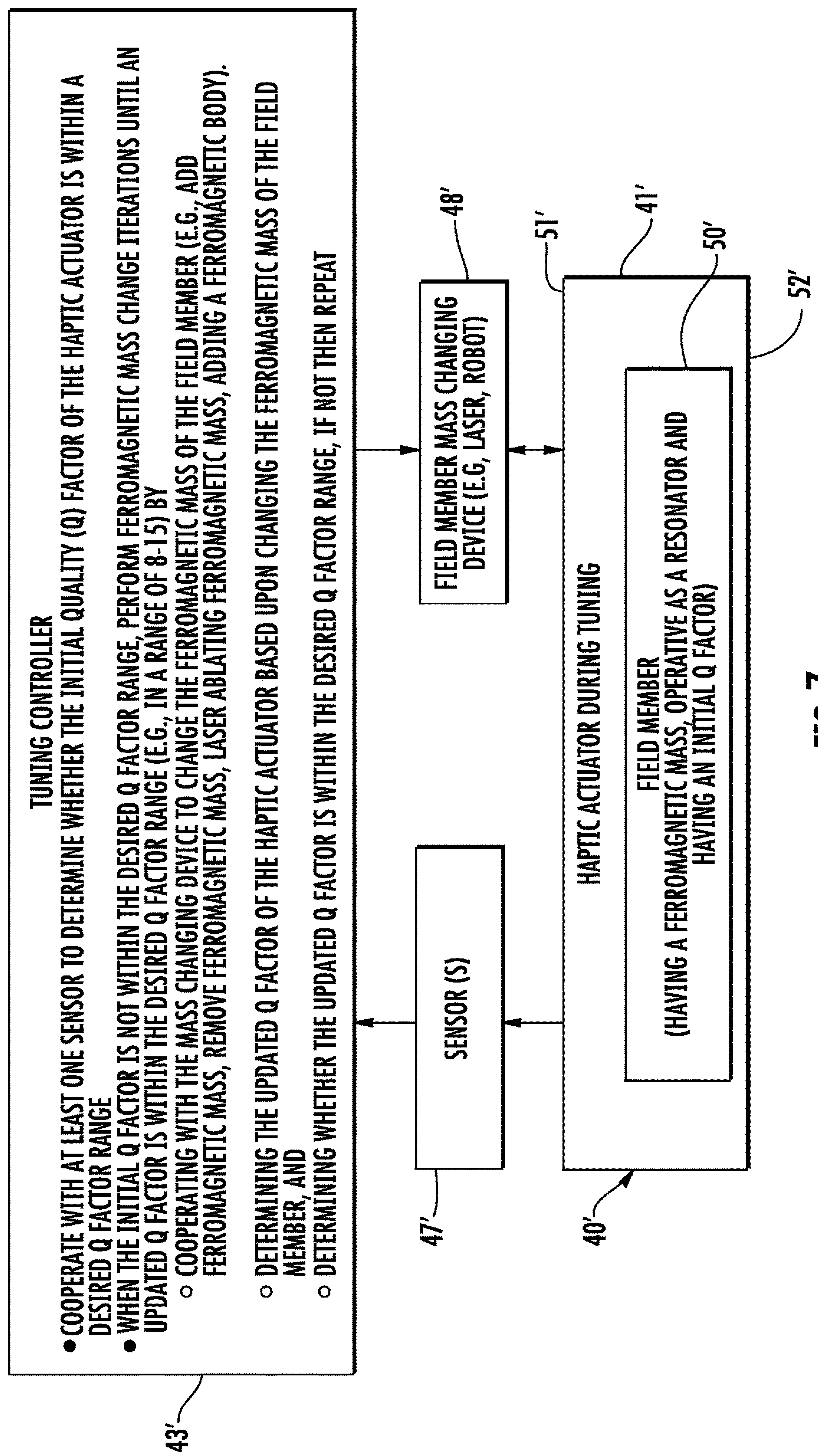

TUNING CONTROLLER
● COOPERATE WITH AT LEAST ONE SENSOR TO DETERMINE WHETHER THE INITIAL QUALITY (Q) FACTOR OF THE HAPTIC ACTUATOR IS WITHIN A DESIRED Q FACTOR RANGE
● WHEN THE INITIAL Q FACTOR IS NOT WITHIN THE DESIRED Q FACTOR RANGE, PERFORM FERROMAGNETIC MASS CHANGE ITERATIONS UNTIL AN UPDATED Q FACTOR IS WITHIN THE DESIRED Q FACTOR RANGE (E.G., IN A RANGE OF 8-15) BY
○ COOPERATING WITH THE MASS CHANGING DEVICE TO CHANGE THE FERROMAGNETIC MASS OF THE FIELD MEMBER (E.G., ADD FERROMAGNETIC MASS, REMOVE FERROMAGNETIC MASS, LASER ABLATING FERROMAGNETIC MASS, ADDING A FERROMAGNETIC BODY).
○ DETERMINING THE UPDATED Q FACTOR OF THE HAPTIC ACTUATOR BASED UPON CHANGING THE FERROMAGNETIC MASS OF THE FIELD MEMBER, AND
○ DETERMINING WHETHER THE UPDATED Q FACTOR IS WITHIN THE DESIRED Q FACTOR RANGE, IF NOT THEN REPEAT
43'
FIELD MEMBER MASS CHANGING DEVICE (E.G, LASER, ROBOT)
48'
SENSOR (S)
47'
HAPTIC ACTUATOR DURING TUNING
41'
51'
52'
40'
FIELD MEMBER
(HAVING A FERROMAGNETIC MASS, OPERATIVE AS A RESONATOR AND HAVING AN INITIAL Q FACTOR)
50'

FIG. 7

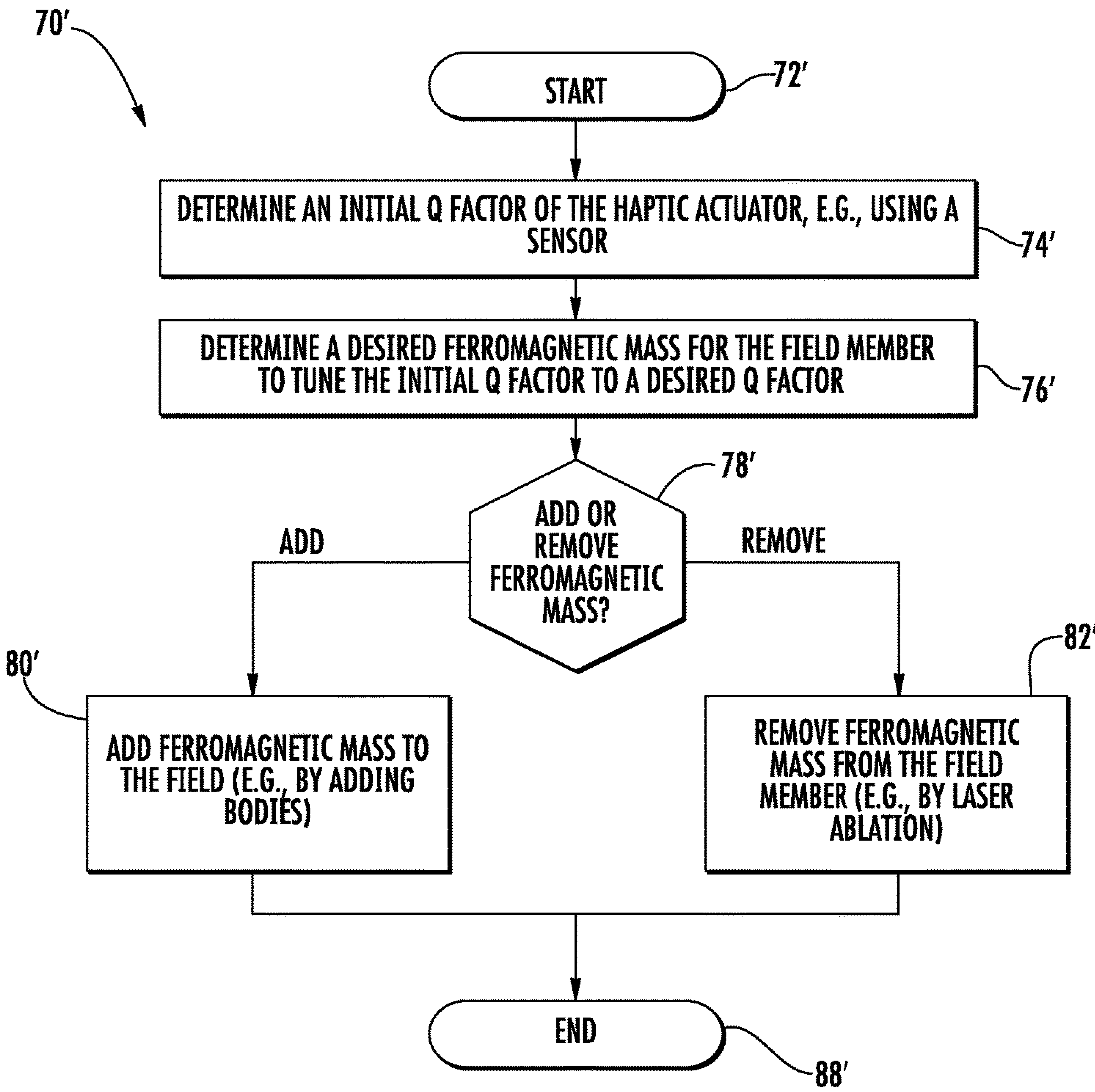

70'
START
72'
DETERMINE AN INITIAL Q FACTOR OF THE HAPTIC ACTUATOR, E.G., USING A SENSOR
74'
DETERMINE A DESIRED FERROMAGNETIC MASS FOR THE FIELD MEMBER TO TUNE THE INITIAL Q FACTOR TO A DESIRED Q FACTOR
76'
78'
ADD OR REMOVE FERROMAGNETIC MASS?
ADD
REMOVE
80'
82'
ADD FERROMAGNETIC MASS TO THE FIELD (E.G., BY ADDING BODIES)
REMOVE FERROMAGNETIC MASS FROM THE FIELD MEMBER (E.G., BY LASER ABLATION)
END
88'

FIG. 8

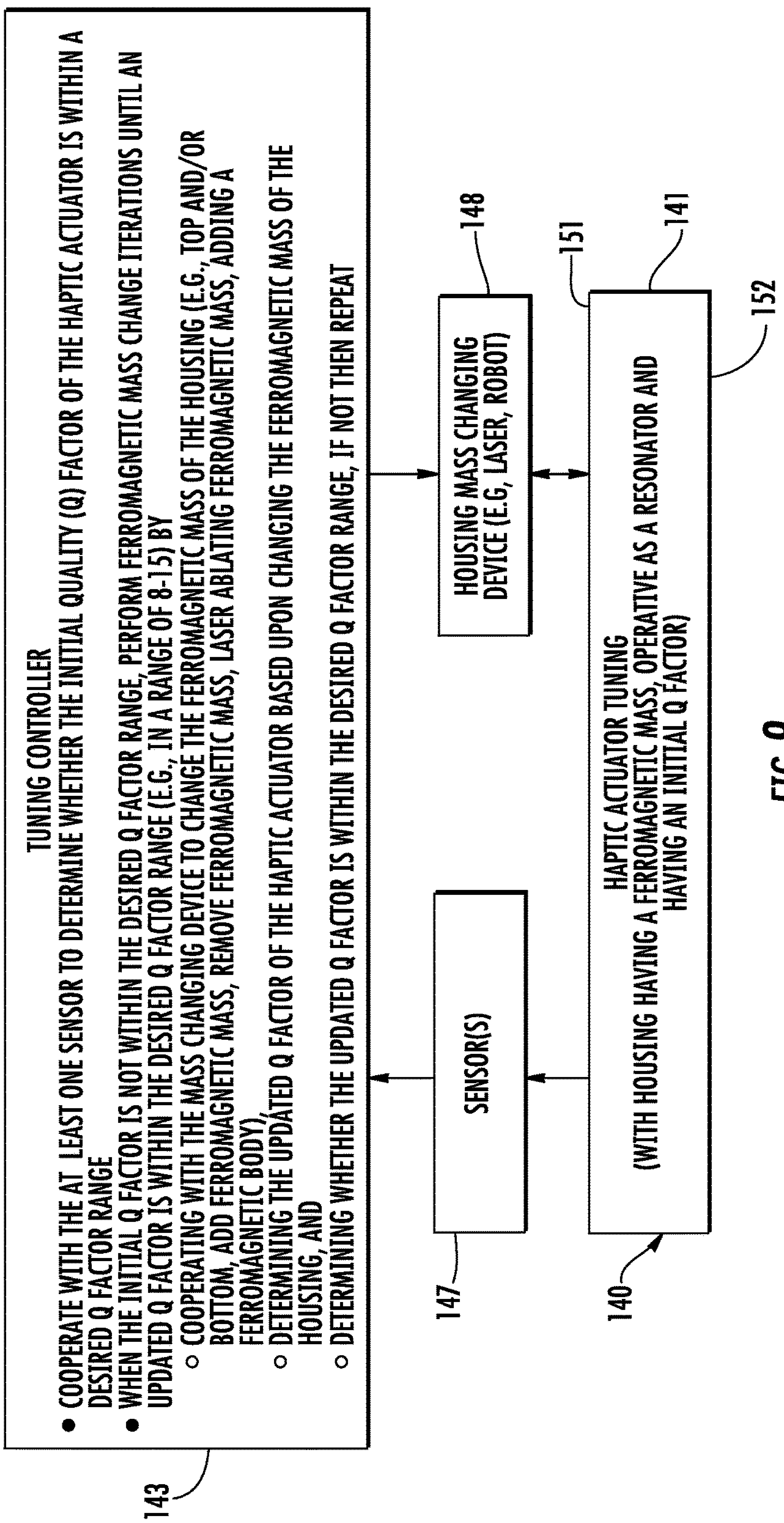

TUNING CONTROLLER
• COOPERATE WITH THE AT LEAST ONE SENSOR TO DETERMINE WHETHER THE INITIAL QUALITY (Q) FACTOR OF THE HAPTIC ACTUATOR IS WITHIN A DESIRED Q FACTOR RANGE
• WHEN THE INITIAL Q FACTOR IS NOT WITHIN THE DESIRED Q FACTOR RANGE, PERFORM FERROMAGNETIC MASS CHANGE ITERATIONS UNTIL AN UPDATED Q FACTOR IS WITHIN THE DESIRED Q FACTOR RANGE (E.G., IN A RANGE OF 8-15) BY
○ COOPERATING WITH THE MASS CHANGING DEVICE TO CHANGE THE FERROMAGNETIC MASS OF THE HOUSING (E.G., TOP AND/OR BOTTOM, ADD FERROMAGNETIC MASS, REMOVE FERROMAGNETIC MASS, LASER ABLATING FERROMAGNETIC MASS, ADDING A FERROMAGNETIC BODY),
○ DETERMINING THE UPDATED Q FACTOR OF THE HAPTIC ACTUATOR BASED UPON CHANGING THE FERROMAGNETIC MASS OF THE HOUSING, AND
○ DETERMINING WHETHER THE UPDATED Q FACTOR IS WITHIN THE DESIRED Q FACTOR RANGE, IF NOT THEN REPEAT
143
HOUSING MASS CHANGING DEVICE (E.G, LASER, ROBOT)
148
SENSOR(S)
147
HAPTIC ACTUATOR TUNING
(WITH HOUSING HAVING A FERROMAGNETIC MASS, OPERATIVE AS A RESONATOR AND HAVING AN INITIAL Q FACTOR)
140
141
151
152

FIG. 9

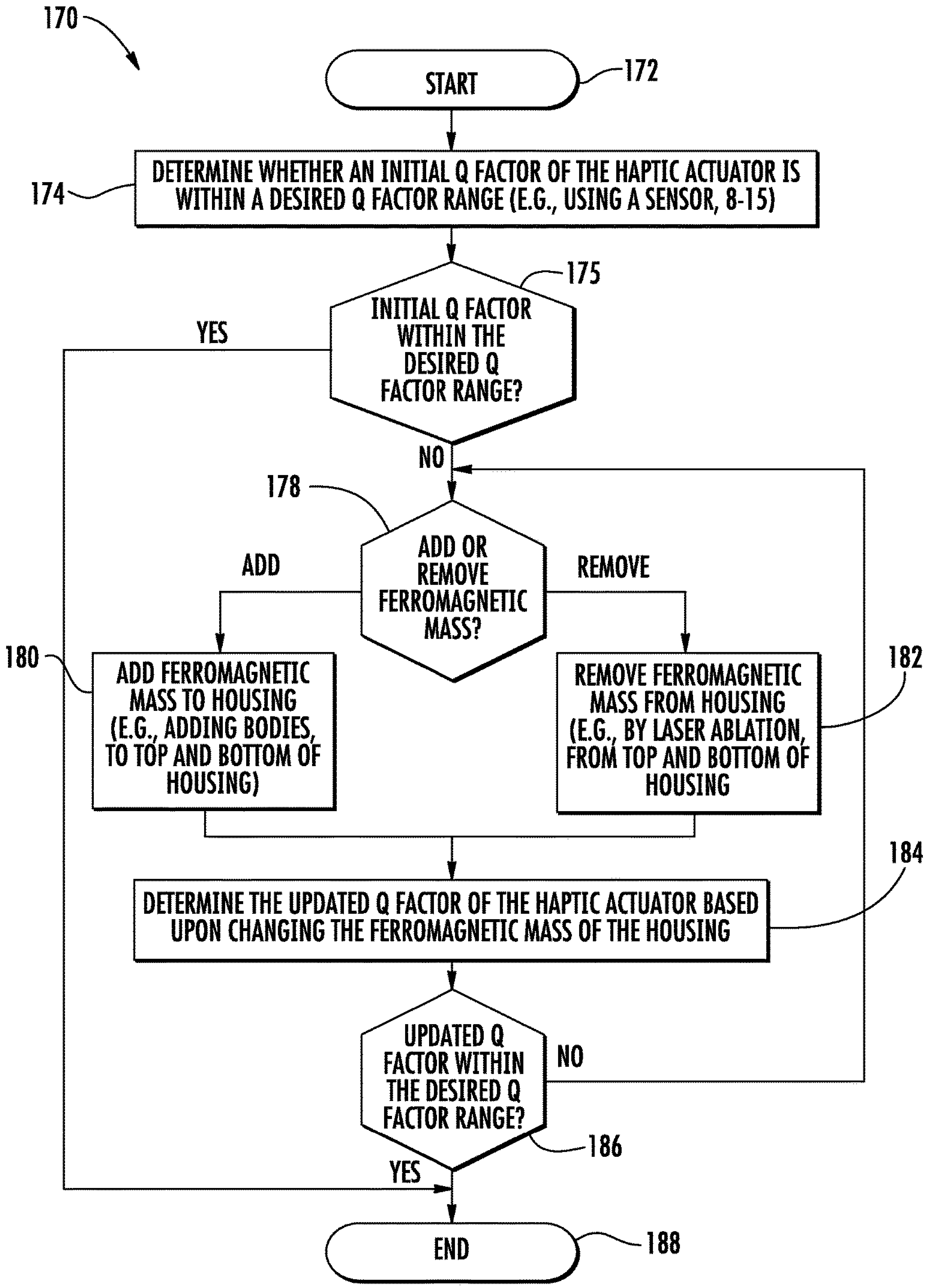

170
START
172
DETERMINE WHETHER AN INITIAL Q FACTOR OF THE HAPTIC ACTUATOR IS WITHIN A DESIRED Q FACTOR RANGE (E.G., USING A SENSOR, 8-15)
174
INITIAL Q FACTOR WITHIN THE DESIRED Q FACTOR RANGE?
175
YES
NO
178
ADD OR REMOVE FERROMAGNETIC MASS?
ADD
REMOVE
180
ADD FERROMAGNETIC MASS TO HOUSING (E.G., ADDING BODIES, TO TOP AND BOTTOM OF HOUSING)
REMOVE FERROMAGNETIC MASS FROM HOUSING (E.G., BY LASER ABLATION, FROM TOP AND BOTTOM OF HOUSING
182
184
DETERMINE THE UPDATED Q FACTOR OF THE HAPTIC ACTUATOR BASED UPON CHANGING THE FERROMAGNETIC MASS OF THE HOUSING
UPDATED Q FACTOR WITHIN THE DESIRED Q FACTOR RANGE?
NO
186
YES
END
188

FIG. 10

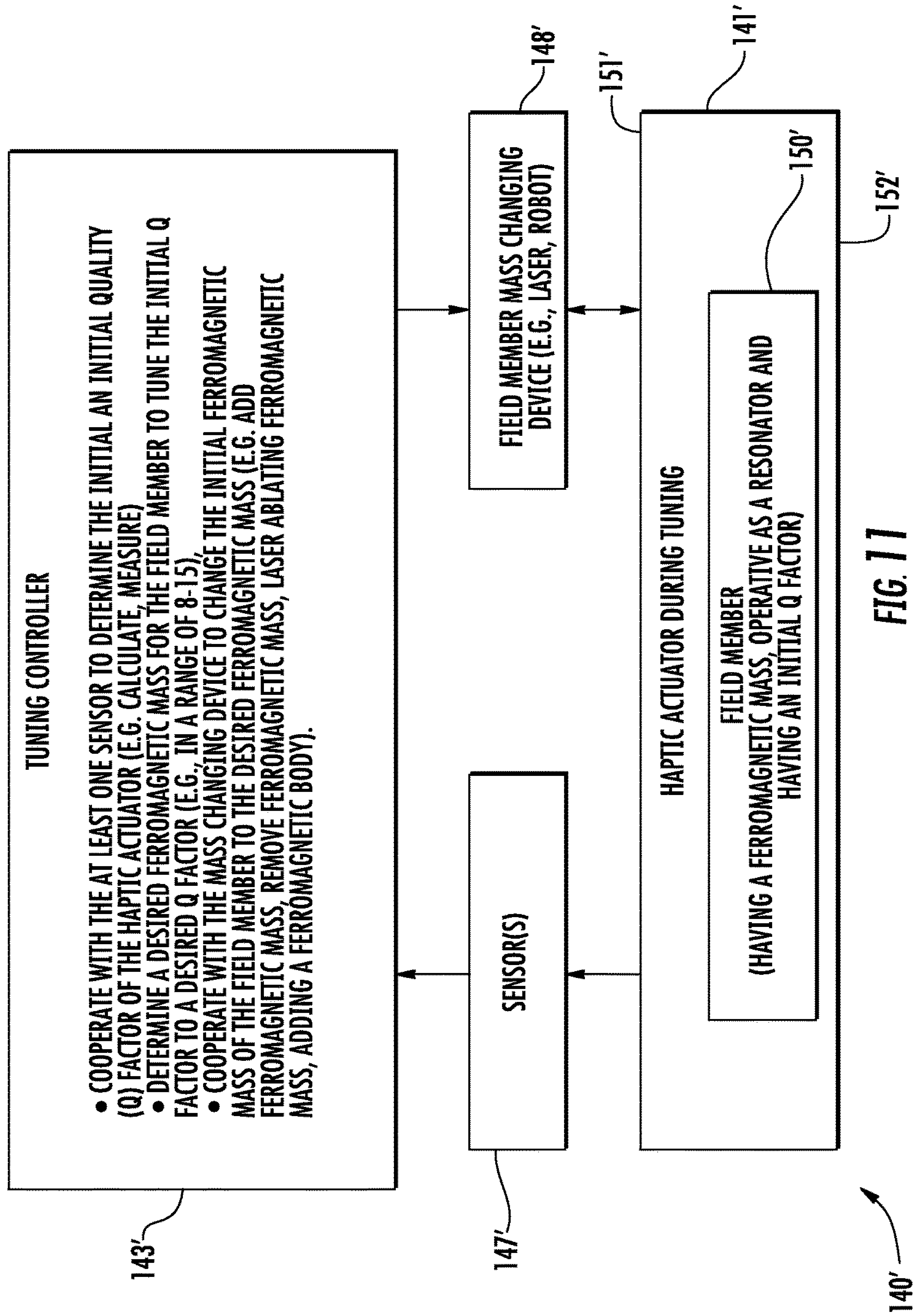

TUNING CONTROLLER
• COOPERATE WITH THE AT LEAST ONE SENSOR TO DETERMINE THE INITIAL AN INITIAL QUALITY (Q) FACTOR OF THE HAPTIC ACTUATOR (E.G. CALCULATE, MEASURE)
• DETERMINE A DESIRED FERROMAGNETIC MASS FOR THE FIELD MEMBER TO TUNE THE INITIAL Q FACTOR TO A DESIRED Q FACTOR (E.G., IN A RANGE OF 8-15).
• COOPERATE WITH THE MASS CHANGING DEVICE TO CHANGE THE INITIAL FERROMAGNETIC MASS OF THE FIELD MEMBER TO THE DESIRED FERROMAGNETIC MASS (E.G. ADD FERROMAGNETIC MASS, REMOVE FERROMAGNETIC MASS, LASER ABLATING FERROMAGNETIC MASS, ADDING A FERROMAGNETIC BODY).
143'
FIELD MEMBER MASS CHANGING DEVICE (E.G., LASER, ROBOT)
148'
SENSOR(S)
147'
HAPTIC ACTUATOR DURING TUNING
141'
151'
152'
FIELD MEMBER
(HAVING A FERROMAGNETIC MASS, OPERATIVE AS A RESONATOR AND HAVING AN INITIAL Q FACTOR)
150'
140'

FIG. 11

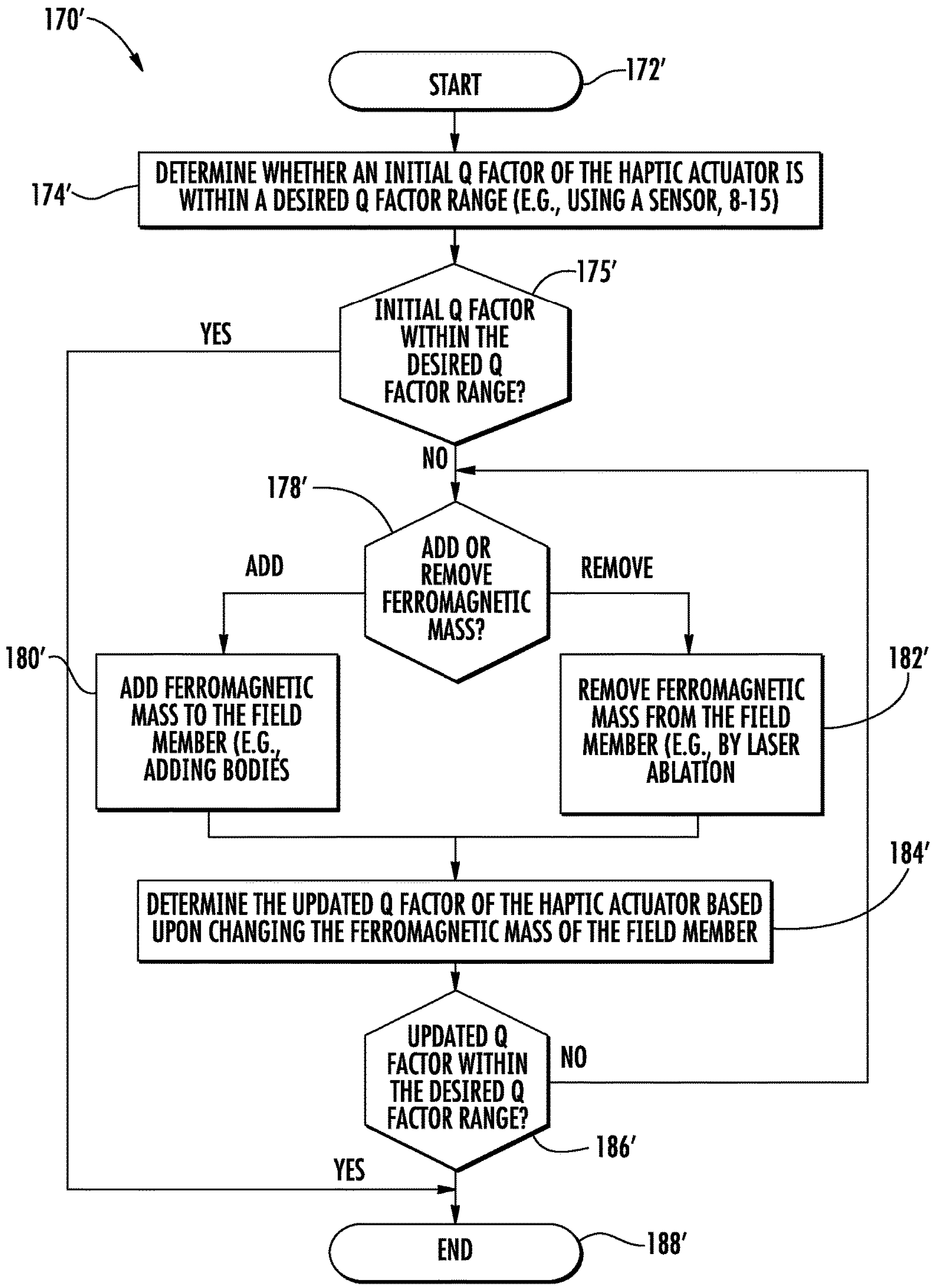

170'
START
172'
DETERMINE WHETHER AN INITIAL Q FACTOR OF THE HAPTIC ACTUATOR IS WITHIN A DESIRED Q FACTOR RANGE (E.G., USING A SENSOR, 8-15)
174'
INITIAL Q FACTOR WITHIN THE DESIRED Q FACTOR RANGE?
175'
YES
NO
178'
ADD OR REMOVE FERROMAGNETIC MASS?
ADD
REMOVE
180'
ADD FERROMAGNETIC MASS TO THE FIELD MEMBER (E.G., ADDING BODIES
182'
REMOVE FERROMAGNETIC MASS FROM THE FIELD MEMBER (E.G., BY LASER ABLATION
184'
DETERMINE THE UPDATED Q FACTOR OF THE HAPTIC ACTUATOR BASED UPON CHANGING THE FERROMAGNETIC MASS OF THE FIELD MEMBER
UPDATED Q FACTOR WITHIN THE DESIRED Q FACTOR RANGE?
NO
186'
YES
END
188'

FIG. 12

METHOD OF TUNING A HAPTIC ACTUATOR INCLUDING FERROMAGNETIC MASS CHANGE ITERATIONS AND RELATED APPARATUS

TECHNICAL FIELD

The present disclosure relates to the field of electronics, and, more particularly, to the field of haptics.

BACKGROUND

Haptic technology is becoming a more popular way of conveying information to a user. Haptic technology, which may simply be referred to as haptics, is a tactile feedback based technology that stimulates a user's sense of touch by imparting relative amounts of force to the user.

A haptic device or haptic actuator is an example of a device that provides the tactile feedback to the user. In particular, the haptic device or actuator may apply relative amounts of force to a user through actuation of a mass that is part of the haptic device. Through various forms of tactile feedback, for example, generated relatively long and short bursts of force or vibrations, information may be conveyed to the user.

SUMMARY

A method of tuning a haptic actuator may include a housing having a ferromagnetic mass, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil. The haptic actuator may be operative as a resonator and having an initial quality (Q) factor. The method may include determining whether the initial Q factor is within a desired Q factor range. The method may also include, when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range. The at least one ferromagnetic mass change iteration may include changing the ferromagnetic mass of the housing, determining the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the housing, and determining whether the updated Q factor is within the desired Q factor range. Accordingly, the haptic actuator may be tuned to a desired Q factor range, for example, to reduce friction caused by misalignments and/or non-uniformity of magnetic forces, the reduced friction of which may reduce failure rates of the haptic actuator.

Changing the ferromagnetic mass of the housing may include adding ferromagnetic mass to the housing. Changing the ferromagnetic mass of the housing may include removing ferromagnetic mass from the housing. Removing ferromagnetic mass from the housing may include laser ablating ferromagnetic mass from the housing, for example.

Changing the initial ferromagnetic mass of the housing may include adding a ferromagnetic body to the housing, for example. The desired Q factor range may be between 8 and 15, for example.

The housing may have a top and a bottom. Changing the ferromagnetic mass of the housing may include changing the ferromagnetic mass of one of the top and bottom of the housing, for example. The field member may include at least one permanent magnet and at least one mass coupled thereto.

Another method aspect is directed to method of tuning a haptic actuator that may include a housing, at least one coil

carried by the housing, and a field member movable within the housing responsive to the at least one coil and having a ferromagnetic mass. The haptic actuator may be operative as a resonator and having an initial quality (Q) factor. The method may include determining whether the initial Q factor is within a desired Q factor range. The method may also include, when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range. The at least one ferromagnetic mass change iteration may include changing the ferromagnetic mass of the field member, determining the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the field member, and determining whether the updated Q factor is within the desired Q factor range.

A device aspect is directed to an apparatus for tuning a haptic actuator that includes a housing having a ferromagnetic mass, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil. The haptic actuator is operative as a resonator and having an initial quality (Q) factor. The apparatus may include at least one sensor, a mass changing device, and a controller. The controller may be capable of cooperating with the at least one sensor to determine whether the initial Q factor is within a desired Q factor range, and when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range. The at least one ferromagnetic mass change iteration may include cooperating with the mass changing device to change the ferromagnetic mass of the housing, cooperating with the at least one sensor to determine the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the housing, and determining whether the updated Q factor is within the desired Q factor range.

Another device aspect is directed to an apparatus for tuning a haptic actuator that includes a housing, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil and having a ferromagnetic mass. The haptic actuator is operative as a resonator and having an initial quality (Q) factor. The apparatus may include at least one sensor, a mass changing device, and a controller. The controller may be capable of cooperating with the at least one sensor to determine whether the initial Q factor is within a desired Q factor range, and when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range. The at least one ferromagnetic mass change iteration may include cooperating with the mass changing device to change the ferromagnetic mass of the field member, cooperating with the at least one sensor to determine the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the field member, and determining whether the updated Q factor is within the desired Q factor range.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an electronic device including a haptic actuator according to an embodiment.

FIG. **2** is a schematic block diagram of the electronic device of FIG. **1**.

FIG. **3** is a schematic side view of the haptic actuator of FIG. **1**.

FIG. **4** is schematic block diagram of an apparatus for tuning a haptic actuator according to an embodiment.

FIG. **5** is a flow diagram illustrating a method of tuning a haptic actuator using the apparatus of FIG. **4**.

FIG. **6** is a graph of illustrating simulated momentum of an untuned haptic actuator and an untuned haptic actuator according to an embodiment.

FIG. **7** is a schematic block diagram of an apparatus for tuning a haptic actuator according to another embodiment.

FIG. **8** is a flow diagram illustrating a method of tuning a haptic actuator using the apparatus of FIG. **7**.

FIG. **9** is a schematic block diagram of an apparatus for tuning a haptic actuator according to another embodiment.

FIG. **10** is a flow diagram illustrating a method of tuning a haptic actuator using the apparatus of FIG. **9**.

FIG. **11** is a schematic block diagram of an apparatus for tuning a haptic actuator according to another embodiment.

FIG. **12** is a flow diagram illustrating a method of tuning a haptic actuator using the apparatus of FIG. **11**.

DETAILED DESCRIPTION

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout and prime notation and numerals in increments of 100 are used to refer to like elements in different embodiments.

Referring initially to FIGS. **1** and **2**, an electronic device **20** illustratively includes a device housing **21** and a controller **22** carried by the device housing. The electronic device **20** is illustratively a mobile wireless communications device, for example, a wearable wireless communications device, and includes a band **28** or strap for securing it to a user. The electronic device **20** may be another type of electronic device, for example, a cellular telephone, a tablet computer, a laptop computer, etc.

Wireless communications circuitry **25** (e.g. cellular, WLAN Bluetooth, etc.) is also carried within the device housing **21** and coupled to the controller **22**. The wireless communications circuitry **25** cooperates with the controller **22** to perform at least one wireless communications function, for example, for voice and/or data. In some embodiments, the electronic device **20** may not include wireless communications circuitry **25**.

A display **23** is also carried by the device housing **21** and is coupled to the controller **22**. The display **23** may be a liquid crystal display (LCD), for example, or may be another type of display, as will be appreciated by those skilled in the art.

Finger-operated user input devices **24***a*, **24***b*, illustratively in the form of a pushbutton switch and a rotary dial are also carried by the device housing **21** and is coupled to the controller **22**. The pushbutton switch **24***a* and the rotary dial **24***b* cooperate with the controller **22** to perform a device function in response to operation thereof. For example, a device function may include a powering on or off of the electronic device **20**, initiating communication via the wireless communications circuitry **25**, and/or performing a menu function.

The electronic device **20** illustratively includes a haptic actuator **40**. The haptic actuator **40** is coupled to the controller **22** and provides haptic feedback to the user in the form of relatively long and short vibrations or "taps", particularly when the user is wearing the electronic device **20**. The vibrations may be indicative of a message received, and the duration of the vibration may be indicative of the type of message received. Of course, the vibrations may be indicative of or convey other types of information. More particularly, the controller **22** applies a voltage to move a moveable body or masses between first and second positions.

While a controller **22** is described, it should be understood that the controller **22** may include one or more of a processor and other circuitry to perform the functions described herein.

Referring now additionally to FIG. **3**, the haptic actuator **40** includes an actuator housing **41** and a coil **44** carried by the actuator housing. Of course, there may be more than one coil carried by the housing **41**. The actuator housing **41** includes ferromagnetic material.

A field member **50** is movable within the housing **21** responsive to the coil **44**. The movement of the field member **50** creates the haptic feedback, or tapping, as will be appreciated by those skilled in the art. While the movement of the field member **50** may be described as being moveable in one direction, i.e., a linear haptic actuator, it should be understood that in some embodiments, the field member may be movable in other directions, i.e., an angular haptic actuator, or may be a combination of both a linear and an angular haptic actuator. The field member **50** may include a mass **57**. The mass **57** may be shaped for or have a particular mass amount for a particular haptic sensation or desired application. Of course, there may be more than one mass **57**.

The field member **50** also includes a permanent magnet **46** adjacent the coil **44**. More than one permanent magnet **46** may be included. The permanent magnet **46** is illustratively coupled to the mass **57**.

It should be understood that in some embodiments, the electromagnetic (or coil **44**) may be swapped with the permanent magnet **46**. In other words, the field member may include the coil **44** and the mass **57** that is movable within the housing **21** and the permanent magnet may be stationary within the housing.

The haptic actuator **40** also includes biasing members between the field member **50** and the actuator housing **41**, which are illustratively in the form of springs **61***a*, **61***b* defining part of a suspension system. The biasing members may be other types of biasing members, for example, coil springs, leaf springs, and flexures. The springs may also or additionally include magnetic springs that, through interaction with the permanent magnet(s) **46** and/or ferritic parts of the actuator housing **41**, if any, store and amplify the energy in the form of elastic/magnetic energy. The springs **61***a*, **61***b* provide biasing of the field member in an initial at-rest position.

The suspension system may also include shafts, linear/angular bearings, sliding bearings, flexures, multi-bar linkage mechanisms, and other springs that may enable motion of the field member **50** in the desired direction (e.g. X axis in a linear actuator or around a certain axis in an angular actuator) while constraining motion in other degrees of freedom. The suspension system may include other and/or additional components for maintaining the suspension of the field member **50** as well as constrain movement of the field member.

The haptic actuator **40** also includes mechanical limit stops **45***a*, **45***b* defined between the housing **41** and the field member **50**. The mechanical limit stops **45***a*, **45***b* limit the movement of the field member to a desired range and/or stop the field member **50**. It will be appreciated by those skilled in the art that the mechanical limit stops **45***a*, **45***b* can be separate from actuator housing **41** or part of the actuator housing.

As will be appreciated by those skilled in the art, the haptic actuator is operative as a resonator, and has an initial quality (Q). A Q factor is a dimensionless parameter that describes the damping of a resonator and characterizes its bandwidth relative to its center frequency. The Q factor of the haptic actuator **40** may change over time. For example, dropping the haptic actuator **40** may cause a change in the Q factor. The performance of the haptic actuator **40** may also be significantly impacted by any imperfection in part geometry, material properties, and assembly, which may make production yield relatively low and relatively expensive.

Moreover, even a "perfect" haptic actuator (e.g. at the actuator level) may become problematic (e.g. noisy, sticky, etc.) after installation in the system as a result of interactions (mechanical, magnetic, etc) between the actuator and system or electronic device (e.g., dropping as noted above).

However, it may be not be feasible to replace the haptic actuator after being assembled in the electronic device. After assembly in the electronic device, any problem with the haptic actuator (e.g., loud acoustic noise, stiction, low Q factor) would generally mean failure of the system.

A friction force generally comes from the imbalance of the force on the moving part (i.e., field member **50**) of the haptic actuator as a result of misalignment of parts and assembly, non uniformity of magnetic forces, etc. As a result of this imbalance/misalignment, a normal force may be exerted, for example, by any bearings, and proportionally, a friction force on the field member **50**. This increased friction force may be the dominant damping force and may determine the Q factor, breakaway voltage, and how "sticky" any vibe is. Accordingly, if the total force is reduced, for example, by compensating for the misalignment forces with external forces, and/or changing the magnetic boundary condition, the forces may be balanced to reduce any friction.

Referring now additionally to FIG. **4** and the flowchart **70** in FIG. **5**, an apparatus and method for tuning the haptic actuator **40** to a desired Q factor, for example, post-assembly, will now be described. Beginning at Block **72**, the method includes, at Block **74**, determining the initial Q factor of the haptic actuator **40**. This may be done with a sensor **47** coupled to a tuning controller **43**. The sensor **47** may measure one or more parameters of the haptic actuator **40** which may be used by the tuning controller **43** to calculate the initial Q factor. More than one sensor **47** may be used to determine the initial Q factor.

At Block **76**, using the tuning controller **43**, a desired ferromagnetic mass is determined for the actuator housing **41** to tune the initial Q factor to a desired Q factor. The desired Q factor may be predetermined based upon the type of haptic actuator, for example. The desired Q factor may be between 8 and 15, for example. Other Q factor ranges may be desired, for example, based upon the type, shape, and application of the haptic actuator.

The tuning controller **43** cooperates with a mass changing device **48** to change the initial ferromagnetic mass of the actuator housing **41** to the desired ferromagnetic mass. More particularly, at Block **78**, the tuning controller **43** determines whether the initial ferromagnetic mass of the housing is to be increased or decreased. Where it has been determined that the initial ferromagnetic mass is to be increased (Block **78**), the tuning controller **43** cooperates with the mass changing device **48** to add ferromagnetic mass, for example in the form of ferromagnetic bodies **37** (FIG. **3**), to the actuator housing **41** (Block **80**). In some embodiments, ferromagnetic mass may be added to top **51** and/or bottom **52** of the actuator housing **41** which may include ferromagnetic material, for example. The corresponding mass changing device **48** may be a device that positions and secures the ferromagnetic bodies **37** to the actuator housing **41**, for example, at one or more locations, for example, at the corners, that may affect the ferromagnetic mass to achieve the desired Q factor. Of course, ferromagnetic mass may be added anywhere on the actuator housing **41**. The process of adding ferromagnetic mass to the actuator housing **41** may be conceptually described along the lines of adding weights to tires of an automobile for balancing the tire.

Where it has been determined that the initial ferromagnetic mass is to be decreased (Block **78**), the tuning controller **43** cooperates with the mass changing device **48** to remove ferromagnetic mass from the actuator housing **41** (Block **82**) leaving a recess **38** (FIG. **3**) in the housing. The corresponding mass changing device **48** may be a laser, for example, for laser ablating portions of the actuator housing **41**. Ferromagnetic mass may be removed at one or more locations that may affect the ferromagnetic mass to achieve the desired Q factor, for example, from the top **51** and/or bottom **52** of the actuator housing **41**, which may include ferromagnetic material. The portions of the actuator housing **41** to be laser ablated may be predetermined, for example, the corners of the actuator housing **41**. Of course, ferromagnetic mass may be removed from anywhere on the actuator housing **41**.

In some embodiments, ferromagnetic mass may be added to one side or portion of the actuator housing **41** while ferromagnetic mass may be removed from another side or portion of the actuator housing to achieve the desired Q factor. The method ends at Block **88**.

Simulations were conducted using haptic actuators that had a relatively large misalignment force that reduced the effective Q factor from ~14 down to 4-7. During simulations, a relatively small magnet was added to the actuator housing. The position of the small magnet was moved until a relatively large, for example, a maximized, Q factor was achieved. Thus, an effective Q factor of 12.5 was able to be achieved (friction Q of 80-120 considering the electromechanical damping) or basically almost no friction in comparison with EM damping.

Referring to the graph **55** in FIG. **6**, the line **56** shows the simulated momentum for haptic actuator without tuning, while the line **58** shows the same simulated momentum for haptic actuator with tuning. Illustratively, the friction force and breakaway voltage is reduced by an order of magnitude and haptic actuator oscillates down to relatively small amplitude.

Referring now to FIG. **7** and the flowchart **70'** in FIG. **8**, another embodiment of an apparatus and method for tuning the haptic actuator **40'** to a desired Q factor will now be described. Beginning at Block **72'**, the method includes, at Block **74'**, determining the initial Q factor of the haptic actuator **40'**. This may be done with the sensor **47'** coupled to a tuning controller **43'** as described above.

At Block **76'**, using the tuning controller **43'**, a desired ferromagnetic mass is determined for the field member **50'** to tune the initial Q factor to a desired Q factor. The desired Q factor may be predetermined based upon the type of haptic actuator, for example. The desired Q factor may be between

8 and 15, for example. Other Q factor ranges may be desired, for example, based upon the type, shape, and application of the haptic actuator.

The tuning controller **43'** cooperates with a mass changing device **48'** to change the initial ferromagnetic mass of the field member **50'** to the desired ferromagnetic mass. More particularly, at Block **78'**, the tuning controller **43'** determines whether mass is to be added or removed from the field member **50'** relative to the initial ferromagnetic mass. Where it has been determined that the initial ferromagnetic mass is to be increased (Block **78'**), the tuning controller **43'** cooperates with the mass changing device **48'** to add ferromagnetic mass, for example in the form of ferromagnetic bodies, to the field member **50'** (Block **80'**). The corresponding mass changing device **48'** may be a device that positions and secures the ferromagnetic bodies to the field member **50'**, for example, at one or more locations, for example, the corners, that may affect the ferromagnetic mass to achieve the desired Q factor. Of course, ferromagnetic mass may be added anywhere on the field member **50'**.

Where it has been determined that the initial ferromagnetic mass is to be decreased (Block **78'**), the tuning controller **43'** cooperates with the mass changing device **48'** to remove ferromagnetic mass from the field member **50'** (Block **82'**). The corresponding mass changing device **48'** may be a laser, for example, for laser ablating portions of the field member **50'**. Ferromagnetic mass may be removed at one or more locations that may affect the ferromagnetic mass to achieve the desired Q factor. The portions of the field member **50'** to be laser ablated may be predetermined, for example.

In some embodiments, ferromagnetic mass may be added to one side or portion of the field member **50'** while ferromagnetic mass may be removed from another side or portion of the field member to achieve the desired Q factor. The method ends at Block **88'**.

Referring now additionally to FIG. **9** and the flowchart **170** in FIG. **10**, another apparatus and method for tuning the haptic actuator **140** to a desired Q factor, for example, post-assembly, will now be described. Beginning at Block **172**, the method includes, at Block **174**, determining whether the initial Q factor of the haptic actuator **140** is within a desired Q factor range. This may be done with a sensor **147** coupled to a tuning controller **143**. The sensor **147** may measure one or more parameters of the haptic actuator **140** which may be used by the tuning controller **143** to calculate the initial Q factor. More than one sensor **147** may be used to determine the initial Q factor.

Similarly to the embodiments described above, a desired Q factor range may be determined based upon the type of haptic actuator, for example. The desired Q factor may be between 8 and 15, for example. Other Q factor ranges may be desired, for example, based upon the type, shape, and application of the haptic actuator.

If the initial Q factor is not within the desired Q factor range (Block **175**), the tuning controller **143** performs ferromagnetic change iterations until an updated Q factor is within the desired Q factor range. When the initial Q factor is not within the desired Q factor range (Block **175**), the tuning controller **143** cooperates with the mass changing device **148** to change the ferromagnetic mass of the actuator housing **141**.

Where it has been determined that the ferromagnetic mass is to be increased (Block **178**), the tuning controller **143** cooperates with the mass changing device **148** to add ferromagnetic mass, for example in the form of a ferromagnetic body to the actuator housing **141** (Block **180**). Ferromagnetic mass may be added to the top **151** and/or bottom **152** of the actuator housing **141**, which may include ferromagnetic material. The corresponding mass changing device **148** may be a device that positions and secures ferromagnetic bodies to the actuator housing **141**, for example, at a given location, for example, the corners, that may affect the ferromagnetic mass to more closely achieve the desired Q factor. Of course, ferromagnetic mass may be added anywhere on the actuator housing **141**.

Where it has been determined that the initial ferromagnetic mass is to be decreased (Block **178**), the tuning controller **143** cooperates with the mass changing device **148** to remove ferromagnetic mass from the actuator housing **141** (Block **182**). The corresponding mass changing device **148** may be a laser, for example, for laser ablating portions of the actuator housing **141**. Ferromagnetic mass may be removed at a given location that may affect the ferromagnetic mass to more closely achieve the desired Q factor, for example, from the top **151** and/or bottom **152** of the actuator housing **141**, which may include ferromagnetic material. The portions of the actuator housing **141** to be laser ablated may be predetermined, for example, the corners of the actuator housing. Of course, ferromagnetic mass may be removed from anywhere on the actuator housing **141**.

In some embodiments, ferromagnetic mass may be added to one side or portion of the actuator housing **141** while ferromagnetic mass may be removed from another side or portion of the actuator housing to achieve the desired Q factor.

Each iteration also includes, at Block **184**, determining, using the tuning controller **143**, the updated Q factor of the haptic actuator **140** based upon the changing of the ferromagnetic mass of the actuator housing **141**. At Block **186**, each iteration also includes determining, using the tuning controller **143**, whether the updated Q factor is within the desired Q factor range. If the updated Q factor is within the desired Q factor range (Block **186**), the method ends at Block **188**. Otherwise, if the updated Q factor is not within the desired Q factor range, another iteration is performed (Block **178**) including changing the ferromagnetic mass of the actuator housing **141** (Blocks **180**, **182**), determining another updated Q factor of the haptic actuator based upon the further changing of the ferromagnetic mass of the actuator housing **141** (Block **184**), and determining whether the further updated Q factor is within the desired Q factor range (Block **186**). It should be understood that, with each iteration, ferromagnetic mass may be added or removed at a different location. For example, if ferromagnetic mass is to be added, each iteration may add a fixed size ferromagnetic body at different locations (e.g., on the corners, top, and/or bottom) on the actuator housing **141**. Alternatively, if ferromagnetic mass is to be removed, segments of a fixed size may be removed from different locations (e.g., on the corners, top, and/or bottom) on the actuator housing **141**. The process or iterations continue until the Q factor is within the desired Q factor range. The method ends at Block **188**.

Referring now additionally to FIG. **11** and the flowchart **170'** in FIG. **12**, another apparatus and method for tuning the haptic actuator **140'** to a desired Q factor, for example, post-assembly, will now be described. Beginning at Block **172'**, the method includes, at Block **174'**, determining whether the initial Q factor of the haptic actuator **140'** is within a desired Q factor range. This may be done with a sensor **147'** coupled to a tuning controller **143'**. The sensor **147'** may measure one or more parameters of the haptic actuator **140'** which may be used by the tuning controller

143' to calculate the initial Q factor. More than one sensor 147' may be used to determine the initial Q factor.

The desired Q factor range may be predetermined based upon the type of haptic actuator, for example. The desired Q factor may be between 8 and 15, for example. Other Q factor ranges may be desired, for example, based upon the type, shape, and application of the haptic actuator.

If the initial Q factor is not within the desired Q factor range (Block **175'**), the tuning controller **143'** performs ferromagnetic change iterations until an updated Q factor is within the desired Q factor range. When the initial Q factor is not within the desired Q factor range (Block **175'**), the tuning controller **143'** cooperates with the mass changing device **148'** to change the ferromagnetic mass of the field member **150'** to the desired ferromagnetic mass.

Where it has been determined that the ferromagnetic mass of the field member **150'** is to be increased (Block **178'**), the tuning controller **143'** cooperates with the mass changing device **148'** to add ferromagnetic mass, for example in the form of a ferromagnetic body to the field member **150'** (Block **182'**). The corresponding mass change device **148'** may be a device that positions and secures ferromagnetic bodies to the field member **150'**, for example, at a given location that may affect the ferromagnetic mass to more closely achieve the desired Q factor. Of course, ferromagnetic mass may be added anywhere on the field member **150'**.

Where it has been determined that the initial ferromagnetic mass is to be decreased (Block **178'**), the tuning controller **143'** cooperates with the mass changing device **148'** to remove ferromagnetic mass, for example, in a given location from the field member **150'** (Block **182'**). The corresponding mass changing device **148'** may be a laser, for example, for laser ablating portions of the field member **150'**. Ferromagnetic mass may be removed at a given location that may affect the ferromagnetic mass to more closely achieve the desired Q factor. Each portion of the field member **150'** to be laser ablated may be predetermined, for example, the corners of the field member. Of course, ferromagnetic mass may be removed from anywhere on the field member **150'**.

Each iteration also includes, at Block **184'**, determining, using the tuning controller **143'**, the updated Q factor of the haptic actuator **140'** based upon the changing of the ferromagnetic mass of the field member **150'**. At Block **186'**, each iteration also includes determining, using the tuning controller **143'**, whether the updated Q factor is within the desired Q factor range. If the updated Q factor is within the desired Q factor range (Block **186'**), the method ends at Block **188'**. Otherwise, if the updated Q factor is not within the desired Q factor range, another iteration is performed (Block **178'**) including changing the ferromagnetic mass of the field member **150'** (Blocks **180'**, **182'**), determining another updated Q factor of the haptic actuator based upon the further changing of the ferromagnetic mass of the field member **150'** (Block **184'**), and determining whether the further updated Q factor is within the desired Q factor range (Block **186'**). It should be understood that, with each iteration, ferromagnetic mass may be added or removed at a different location on the field member **150'**. For example, if ferromagnetic mass is to be added, each iteration may add a fixed size ferromagnetic body at different locations on the field member **150'**. Alternatively, if ferromagnetic mass is to be removed, segments of a fixed size may be removed from different locations on the field member **150'**. The process or iterations continue until the Q factor is within the desired Q factor range. The method ends at Block **188'**.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. A method of tuning a haptic actuator comprising a housing having a ferromagnetic mass, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil, the haptic actuator operative as a resonator and having an initial quality (Q) factor, the method comprising:

determining whether the initial Q factor is within a desired Q factor range; and

when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range, the at least one ferromagnetic mass change iteration comprising

changing, using a mass changing device, the ferromagnetic mass of the housing,

determining the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the housing, and

determining whether the updated Q factor is within the desired Q factor range.

2. The method of claim **1** wherein changing the ferromagnetic mass of the housing comprises adding ferromagnetic mass to the housing.

3. The method of claim **1** wherein changing the ferromagnetic mass of the housing comprises removing ferromagnetic mass from the housing.

4. The method of claim **3** wherein removing ferromagnetic mass from the housing comprises laser ablating ferromagnetic mass from the housing.

5. The method of claim **1** wherein changing the ferromagnetic mass of the housing comprises adding a ferromagnetic body to the housing.

6. The method of claim **1** wherein the desired Q factor range is between 8 and 15.

7. The method of claim **1** wherein the housing has a top and a bottom; and wherein changing the ferromagnetic mass of the housing comprises changing the ferromagnetic mass of one of the top and bottom of the housing.

8. The method of claim **1** wherein the field member comprises at least one permanent magnet and at least one mass coupled thereto.

9. A method of tuning a haptic actuator comprising a housing, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil and having a ferromagnetic mass, the haptic actuator operative as a resonator and having an initial quality (Q) factor, the method comprising:

determining whether the initial Q factor is within a desired Q factor range; and

when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range, the at least one ferromagnetic mass change iteration comprising

changing, using a mass changing device, the ferromagnetic mass of the field member, determining the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the field member, and

determining whether the updated Q factor is within the desired Q factor range.

10. The method of claim **9** wherein changing the ferromagnetic mass of the field member comprises adding ferromagnetic mass to the field member.

11. The method of claim **9** wherein changing the ferromagnetic mass of the field member comprises removing ferromagnetic mass from the field member.

12. The method of claim **11** wherein removing ferromagnetic mass from the field member comprises laser ablating ferromagnetic mass from the field member.

13. The method of claim **9** wherein changing the initial ferromagnetic mass of the field member comprises adding a ferromagnetic body to the field member.

14. The method of claim **9** wherein the desired Q factor range is between 8 and 15.

15. An apparatus for tuning a haptic actuator comprising a housing having an initial ferromagnetic mass, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil, the haptic actuator operative as a resonator and having an initial quality (Q) factor, the apparatus comprising:

at least one sensor;

a mass changing device; and

a controller capable of

cooperating with the at least one sensor to determine whether the initial Q factor is within a desired Q factor range, and

when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range, the at least one ferromagnetic mass change iteration comprising

cooperating with the mass changing device to change the ferromagnetic mass of the housing,

cooperating with the at least one sensor to determine the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the housing, and

determining whether the updated Q factor is within the desired Q factor range.

16. The apparatus of claim **15** wherein the mass changing device is capable of changing the ferromagnetic mass of the housing by adding ferromagnetic mass to the housing.

17. The apparatus of claim **15** wherein the mass changing device is capable of changing the ferromagnetic mass of the housing by removing ferromagnetic mass from the housing.

18. The apparatus of claim **17** wherein the mass changing device is capable of removing ferromagnetic mass from the housing by laser ablating ferromagnetic mass from the housing.

19. The apparatus of claim **15** wherein the mass changing device is capable of changing the ferromagnetic mass of the housing by adding a ferromagnetic body to the housing.

20. The apparatus of claim **15** wherein the mass changing device is capable of changing the ferromagnetic mass of the housing to the desired ferromagnetic mass so that the desired Q factor is in a range between 8 and 15.

21. An apparatus for tuning a haptic actuator comprising a housing having an initial ferromagnetic mass, at least one coil carried by the housing, and a field member movable within the housing responsive to the at least one coil, the haptic actuator operative as a resonator and having an initial quality (Q) factor, the apparatus comprising:

at least one sensor;

a mass changing device; and

a controller capable of

cooperating with the at least one sensor to determine whether the initial Q factor is within a desired Q factor range, and

when the initial Q factor is not within the desired Q factor range, performing at least one ferromagnetic mass change iteration until an updated Q factor is within the desired Q factor range, the at least one ferromagnetic mass change iteration comprising

cooperating with the mass changing device to change the ferromagnetic mass of the field member,

cooperating with the at least one sensor to determine the updated Q factor of the haptic actuator based upon changing the ferromagnetic mass of the field member, and

determining whether the updated Q factor is within the desired Q factor range.

22. The apparatus of claim **21** wherein the mass changing device is capable of changing the ferromagnetic mass of the field member by adding ferromagnetic mass to the field member.

23. The apparatus of claim **21** wherein the mass changing device is capable of changing the ferromagnetic mass of the field member by removing ferromagnetic mass from the field member.

24. The apparatus of claim **23** wherein the mass changing device is capable of removing ferromagnetic mass from the housing by laser ablating ferromagnetic mass from the housing.

25. The apparatus of claim **21** wherein the mass changing device is capable of changing the ferromagnetic mass of the field member by adding a ferromagnetic body to the field member.

26. The apparatus of claim **21** wherein the mass changing device is capable of changing the ferromagnetic mass of the field member to the desired ferromagnetic mass so that the desired Q factor is in a range between 8 and 15.

* * * * *